Fungi for Material Futures: the role of design

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Abstract

The last decade has seen a rapid growth in design interest, research and development of mycelium-based technologies for various applications across textiles, fashion, product, furniture and architecture domains. Building on an ancient relationship between fungi and humankind – well documented by ethnomycology literature and advanced through both biotechnology and creative practice – a new partnership between design, science and industry leaders has pioneered the market introduction of fungi-derived products. The careful crafting of material, aesthetic and performance properties, paired with an open, collaborative and conscious approach to material innovation, has meant that the early concept designs, protypes, and commercially realised applications, present a holistically considered future of mycelium products, environments and systems. This chapter charts an overview of key moments, considerations and stakeholders in this growing design domain, with a view to providing a resource for the next generation of innovators, who will advance the scope and future applications of fungi in design.

Keywords

Mycelium · Materials · Innovation · Biodesign · Biofabrication · Design Thinking · Sustainability · Interdisciplinarity

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1.1 Introduction

'We're on a journey to create a more sustainable world. But what if the best way to work for nature was to work with it? And what if the answer was right under our feet…' (adidas, 2021)

Thus begins the launch of *adidas*' latest concept shoe – the *Stan Smith Mylo*^{TM} – a mycelium-based interpretation of their iconic footwear design. The product was launched recently as part of a newly-established fashion consortium between *Stella McCartney*, *adidas*, *lululemon* and *Kering* who, in October 2021, announced an industry-first partnership and investment in consumer biomaterials, to advance the productisation and market realisation of *Mylo*^{TM} (Figure 1). *Mylo*^{TM} is a fungi-derived alternative to leather. It is developed by engineering the vegetative growth of filamentous fungi (mycelium) into material sheets that could be fashioned into a range of fashion and sportswear products.

Figure 1. Mylo^{TM} *'leather' and material swatches. © Bolt Threads*

Mylo^{TM} is only one of a range of mycelium-based design propositions which began to enter textile technology and design realms since the early nineties, and has since gained rapid momentum due to the parallel advances in three key areas:

Science-led companies, e.g., *Ecovative*, *Modern Meadow* and *Bolt Threads* amongst others, have invested effort, talent and resources towards the development and commercialisation of victimless[1] alternatives to animal-based, or ecologically harmful petroleum-based materials and products. This sits well within the growing domains of bioeconomy[2] (Butu *et al.,* 2020; Lee *et al.*, 2020) and circular economy[3] (Meyer *et al.,* 2020), and is in alignment with the objectives of the UN Global Sustainability Goals.

The design community developed a keen interest in exploring novel processes of fabrication, namely biofabrication (Lee *et al.*, 2020), and began collaborating with scientists to *'grow'* design products, as opposed to traditional methods of production that rely heavily on extraction of finite natural resources. Biomaterials, bio-inspired design and biofabrication entered design parlance through the works of designers, such as Suzanne Lee (2005, 2011, 2012), Nancy Tilbury (2009), Carole Collet (2012) and Maurizio Montalti (2010a, 2010b, 2010c) amongst others, who went on to educate and inspire many of today's designers working in this field.

A new type of environmentally and socially conscious, value-driven consumer emerged – one, who would not compromise on the quality of products they buy at the expense of planetary health, and would hold companies accountable to sustainable, transparent and ethical processes of resourcing, manufacturing, supply chain, and end-of-use management (Fletcher, 2008; Fletcher and Grose, 2012; Thackara, 2015).

The parallel development in these areas, an overall change in mindset towards open innovation, collaboration and transparency, and the urgency of the environmental crisis, helped create the right context and time to successfully bring to market mycelium-based materials and products.

The following sections provide a design-focused discussion on the value and applications of fungi for materials and consumer products. This is informed by the author's personal interest and design enquiry in the development of novel bio-based materials for applications in textiles, fashion and furniture.

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[1] 'Victimless Leather' (Catts and Zurr, 2004) was a miniature prototype of a stitch-less jacket grown from immortalised cell lines on a biodegradable polymer matrix which explored the future of lab-grown 'leather'.

[2] The bioeconomy aims to *"reduce the dependence on natural resources, transform manufacturing, promote sustainable production of renewable resources from land, fisheries and aquaculture and their conversion into food, feed, fibre, bio-based products and bio-energy, while growing new jobs and industries".* https://ec.europa.eu/programmes/horizon2020/en/h2020-section/bioeconomy

[3] The circular economy aims to *"redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the system. Underpinned by a transition to renewable energy sources, the circular model builds economic, natural, and social capital."* https://www.ellenmacarthurfoundation.org/circular-economy/concept

Key questions that are explored throughout this chapter, with a view to opening up thinking and opportunities for further collaborative design-science-industry investigation, include:

What are the benefits of introducing fungi-based[4] materials and products? How do we ensure integrity of narrative and market realisation?

Who are the key stakeholders in bringing these products to market? How do we develop an approach that is inclusive of scientific, design, market, corporate and environmental considerations and benefits?

What are the current gaps and opportunity areas in realising a mycelium-based future for consumer products?

What is the value of design thinking, research and practice in advancing engagement with, perception and realisation of consumer biomaterials?

1.2 The beginnings of fungi material innovation

1.2.1 The untapped material potential of the Fungi Kingdom

As a natural resource and raw material for design, fungi appear to be relatively untapped (Cooke, 1977; Deshmukh and Rai, 2005; Kendall, 2013; Stamets, 2004). The diverse kingdom, comprising the well-known mushrooms, toadstools, bracket fungi, moulds, yeasts and lichens, is estimated to include between 2.2 and 3.8 million species, of which less than ten per cent have been described (Willis, 2018). Their varied morphology, natural properties, and existing biotechnological applications (Hamlyn, 1991; Moss, 1987; Singh and Aneja, 1999; Stamets and Chilton, 1983), create scope to consider a multitude of novel uses that bring together mycology, cutting-edge biotechnology, market leaders, and visionary design thinking and craft. As Charaya and Mehrotra (1999) aver, *"In the emerging 'age of biotechnology', the fungi are expected to provide a wider range of useful products and processes for human welfare under the banner of what is called 'fungal biotechnology'".*

The roles fungi play for life on Earth have been predominantly the subject of scientific research. Their importance as plant, animal and human pathogens is well documented, and their beneficial applications have long been developed by biotechnology sectors, for example, in food and beverages production, medicine,

[4] 'Fungi-based' and 'mycelium-based' are used interchangeably throughout this article, as the fungi currently used in design, which are referenced in this publication, are all filamentous.

agriculture, and perfumery (Moss, 1987; Wainwright, 1992). Fungi are key biological factors in sustaining the planet's ecosystem biodiversity and dynamics (Boddy, 2013; Boddy and Coleman, 2010). Their natural properties to recycle carbon, nitrogen and other essential elements that feed the soil, have formed the basis for applications such as mycofiltration, mycoforestry, mycoremediation and mycopesticides, which Stamets (2004) proposes as a means for *"the mycological rescue of the planet"*.

Charaya and Mehrotra (1999) further emphasise the unique properties of fungi that make them an appropriate and useful natural resource for novel products, e.g., their ability to produce a variety of enzymes, conferring upon them the ability to colonise and degrade various substrates; the potential to synthesise a great variety of metabolites; and the large surface area of the hyphae through which fungi can interchange substances with their environment. In circular design, where a major concern is how we keep products in use for longer, or how we recycle and upcycle materials that are already in use, this indicates a beneficial application for upcycling by-products not only from the design industry itself, e.g., from fashion and architecture, but also from agriculture, food and beverage production.

In a global call to action, to unlock the potential of plants and fungi for sustainable development, Antonelli, Smith and Simmonds (2019) assert*: "Humans have been using biodiversity for hundreds of thousands of years, but at no time in our history has it been more crucial to accelerate our exploration of the useful properties of the species that inhabit the world around us."*

For a designer, the access to such an immense and varied resource triggers the imagination of the myriad potential uses for fungi across the design process – from new bio-based raw materials, e.g., fibres and composites, through colour and finishing agents, e.g., pigments as well as enzymes used to treat denim, to a range of consumer products across fashion, architecture and product design. Furthermore, this enables us to completely reimagine processes of fabrication through the adoption of biodesign processes from the biotechnology and medical industries, as well as the entire product lifecycle – on one hand from the consumer perspective, and on the other, from a systems perspective as a new bioeconomy.

1.2.2 A biofabricated future

Since ancient times developments in fabric production, technology and function have been interwoven with the advances of human society (Trochmé, 2002). Historically textile products have been derived from natural plant and animal resources including cotton, linen, wool and silk, which resulted in a well-established, possibly subconscious affinity to materials of natural origin; their physical and aesthetic properties being associated with softness, comfort and luxury: *"[Even] the raw fibre in its natural state is visually evocative of its potential usefulness to man, the small cloud-like formations of the cotton bolls* *suggestive of a comforting end product."* (Hallett and Johnston, 2010)

The multi-disciplinary nature of material and textile production has long triggered the imagination, of both scientists and artists, about how technology and innovation could advance and enrich the composition of our manmade world and everyday objects. Corbman (1985: 310) documents the works of English naturalist Robert Hooke who, in 1664, envisaged that it would be possible to make *"an artificial glutinous composition, much resembling, if not full as good, nay better, than that excrement, or whatever other substance it be out of which the silkworm wire-draws his clew".* Hooke's vision came into realisation through the invention of nitrocellulose by Louis Marie Hilaire Bernigaud de Chardonnet in 1885 as an alternative to silk. This marked the beginning of a line of man-made materials, e.g., viscose rayon (Handley, 1999), which aimed to deliver improved quality and performance at a lower economic cost (Corbman, 1985; Hallett and Johnston, 2010; Trochmé, 2002).

Today, the production of man-made, yet bio-derived materials, is being advanced through the use of biotechnology and biofabrication processes traditionally employed in the biomedical industries (Camere and Karana, 2018; Lee *et al.,* 2020). Camere and Karana (2018) explain that through the use of low-energy processes that harness the natural properties of living systems, growing design[5], or biofabrication, offer a process and resulting materials that *"are not only harmless to the environment and biodegradable, but they can even nurture the cultivation of new materials in their end of life."* Furthermore, Camere and Karana assert that, beyond merely offering a replacement for environmentally harmful plastics, such materials could extend and advance the functionality of traditional objects through meaningful applications for a long-term and sustainable change.

At the turn of the century, the idea of alternative biobased materials began to attract design attention and experimentation. Advances in biotechnology and synthetic biology were inspiring creatives to apply traditional methods of design thinking and craft, to draw upon a new palette of media such as bacteria, skin and bone tissue, algae and moss. This was the beginning of *'bio'* material innovation (Lee *et al.*, 2020), which set out to explore a range of alternative biobased[6]

[5] The material design practice which entails growing materials from living organisms to achieve unique material functions, expressions, and sustainable solutions for product design (Montalti, 2010b; Camere and Karana, 2018)

[6] Biobased materials are *"wholly or partly derived from biomass, such as plants, trees or animals (the biomass can have undergone physical, chemical or biological treatment)"* (https://www.cen.eu/work/areas/chemical/biobased/Pages/default.aspx) and exclude those derived from fossil sources. Traditional examples of biobased materials would include, but are not limited to: natural fibres (e.g., cotton, wool and silk), manmade cellulosics (e.g., viscose), natural polymers (e.g., chitin, keratin and casein), animal leathers and their alternatives, through to polycotton blends (where the biocontent meets the minimum stipulated requirement).

materials. The new media, often *grown* in the design studio, or cultured in the lab where scientific collaboration was possible, presented a new and exciting process of fabrication – *'growing design'* (Camere and Karana, 2018; Montalti, 2010c) as a potential method of self-assembly and material construction resulting in *'biofabricated'* materials and products (see Lee *et al.,* 2020, p.7 for a full list of terms). The concept designs proposed a plethora of new material possibilities, user experiences, production and consumption models.

One of the pioneers in this design domain was Suzanne Lee, who first explored whether one could *'grow'* a material, through experimentation with a kombucha tea fermentation process that dates back to ancient Japanese methods. The idea emerged through conversation with a biologist as part of Lee's research for her book *Fashioning the Future* (2005: Chapter 3), which led to the inception of *BioCouture*. The material – a type of bacterial cellulose – was grown in a vat of the kombucha recipe until a sufficient layer would form on the top, which could be then harvested and either moulded directly into a desirable form, e.g., a tote-bag, or conventionally cut and sewn to create a garment, e.g., a denim jacket. The resulting material resembled the feel and strength of vegetable leather.

To bring to life the potential applications for this novel material in an accessible format, Lee used the bacterial cellulose to recreate iconic fashion articles, e.g., a kimono, a court shoe (Figure 2), bomber and biker jackets. Sustainable methods of decoration, such as vegetable dyeing and oxidation, were applied to mimic the aesthetic and enhance the cultural familiarity and high-street appeal of these artefacts. The familiarity of the finished prototypes helped stakeholders visualise and understand how *BioCouture* could offer a new line of sustainable, organic, biocompostable and biodegradable products to the market (Lee, 2011; Lee, 2012).

Figure 2. BioCouture shoe as exhibited at Alive: New design frontiers (Collet, 2013) © Author's archive

BioCouture, and similar projects exploring processes of fermentation (Franklin and Cass, 2014; Lee, 2011), tissue culture (Catts and Zurr, 2004; Congdon, 2013; Forgacs, 2013; Tilbury, 2009; Thompson, Stott and Kerridge, 2006;) and synthetic biology (Ginsberg and King, 2009-2011, Collet, 2012), raised questions about the meaning of traditional interactions between the human body and clothing, and the moral and ethical considerations around the use of living materials, manipulated or otherwise. They probed what the material makeup of our world post-2050 could be, and highlighted that, in a future where any material could be engineered and programmed at the cellular level, designers had a new role and a great responsibility to bear, as creators of both living and non-living matter.

In light of environmental concerns, sustainability and wellbeing, it was considered that such methods, which built on naturally occurring processes and were advanced by biotechnology, synthetic biology and material science, would require less human labour, fewer natural resources and low-energy production conditions, to be ultimately kinder to the planet and human health.

> *"Forget harvesting fields of cotton then spinning and weaving cloth. Imagine if we could grow clothing. I grow sheets of bacterial-cellulose in a green tea solution to produce a textile material […] My vision is to produce desirable textiles and clothing with the utmost respect for the natural world." (Lee, 2009)*

However, in the two decades between 1990 and 2010, few designers the world over were exploring fungi as a potential resource for design fabrication. In fashion in particular, there are only a few well documented examples from that period.

In 1997, Belgian designer Martin Margiela's presented a series of experimental works for his solo exhibition '9/4/1615' at the *Boijmans van Beuningen Museum* of Rotterdam. In collaboration with a microbiologist, Margiela treated one replica garment from each of his previous collections with bacteria and moulds, as a means of critiquing the transient nature of the fashion industry through the natural cycle of creation and decay on Earth.

Australian designer, Dr Donna Franklin used the mycelium and fruit bodies of the fungus *Pycnoporus coccineus* (orange bracket fungus) to construct a *'living'* dress (Franklin, 2004). The resulting work entitled *'Fibre Reactive'* was exhibited at the *Biennale of Electronic Art Perth* (2004) and the *Second Skin* exhibition at the *Smithsonian Cooper-Hewitt, National Design Museum* (2006) amongst others.

Figure 3. Donna Franklin, 'Fibre Reactive' dress, Pycnoporus coccineus, silk organza, 2004. Photographer: Robert Firth. Image courtesy of SymbioticA

When the author's investigation of fungi as a potential material for fashion and textiles fabrication began in 2010, the idea that one could design an artefact out of mycelium, which would cohabit our everyday environment, or even replace some of the materials we have used for thousands of years, e.g., cotton, was still novel, foreign, and well situated in the *'What if…?'* sections of speculative exhibitions (Ivanova, 2011; Montalti, 2010c).

A pertinent example is Maurizio Montalti's conceptual project *'Continuous Bodies: cycles of decomposition triggering a symbiotic partnership between humans and fungi'* (2010a) which proposed the use of a mycelium shroud as a sustainable medium to decompose the human body when buried, and transform the toxins produced during the process of decay into useful compounds for the soil, thereby including the human being as part of nature's eternal cycle. This speaks directly to the work of Stamets (2004) who calls fungi *"the interface organisms between life and death",* in reference to their natural properties to recycle carbon, nitrogen and other essential elements that in turn feed the soil, trees and other plants.

In product design, artist Phil Ross and designers Maurizio Montalti and Eric Klarenbeek were amongst the first to explore the natural properties of mycelium to decay, bind and solidify matter, to grow furniture and architectural elements, e.g., chairs and building blocks. In 2007, the US company *Ecovative Design LLC* was founded by Eben Bayer and Gavin McIntyre after graduating from *Rensselaer Polytechnic Institute (RPI)*, New York (NY), to exploit the properties of mycelium to self-assemble lignin and cellulose. *Ecovative* used mycelium to transform agricultural byproducts into composite materials which could offer sustainable alternatives to packaging and insulation materials. A more detailed description of the extended practice of Ross, Montalti, Klarenbeek and *Ecovative*, as well as others, is provided in Section 1.3 'Fungi applications in contemporary design'.

1.2.3 Ethnomycology

Much less known are some of the miscellaneous ethnomycological[7] uses of fungi outside of food and medicine, which date back at least 8000 years (Boddy and Coleman, 2010; Dugan, 2011; Harding, 2008; Spooner and Roberts, 2005).

For example, dried fruit bodies of *Haploporus odorus,* which has anise-like smell, were worn as scented body adornment by indigenous people, to enhance manhood and create a spiritual link with the Gods. Shaggy and common inkcaps (*Coprinus comatus* and *Coprinus atramentarius*) were used to manufacture ink. Timber stained in blue-green by the green elfcup (*Chlorociboria aeruginascens*) was incorporated into small saucer-lie objects named Tunbridge ware, after the town of Turnbridge Wells in Kent, UK where they were produced (Collins, 2008; Spooner and Roberts, 2005). *Fomes fomentarius* and other bracket fungi, e.g., the willow bracket *(Pjellinus ignarius),* the birch bracket *(Piptoporous betulinus),* the maze gill *(Datronia mollis)* and the chicken of the woods *(Laetiporus suplhureus),* were used as tinder to carry fire (Harding, 2008). The black shiny rhizomorphs of *Polyporus rhizomorphus* were fashioned into belts in Gabon, and the horse-hair-like hyphae of *Marasmus crinisequi* were used for jewellery strings in Congo and Indonesia (Spooner and Roberts, 2005).

For the benefit of design, such miscellaneous applications provide an invaluable starting point for thinking and development around novel bioconsumer products. A case in point is the suede-like material Amadou, which is derived from the tinder polypore *Fomes fomentarius*. For hundreds of years craftsmen in Hungary, Bohemia and Romania have extracted the inner, fleshy part of the fruitbody, i.e., the fibrous trama (Cooke, 1977; Gandia *et al.,* 2021), and made into sheets of the leather-like material – varying in size depending on the maturity the fruitbody – which were then used to make hats and other wearable artefacts sold at town markets and fares (Boddy and Coleman, 2010; Dugan, 2011; Gandia *et al.,* 2021; Spooner and Roberts, 2005).

The species listed above are some of the fungi that are currently of greatest interest to designers and industry, due to their well-documented beneficial uses and applications. Through a multi-disciplinary exchange in material innovation, what was once taken from nature, as with the *Fomes fomentarius* fruit body to become a

[7] Ethnomycology is a field of studies concerned with the various cultural receptions and uses of fungi by humankind throughout history

hat, could be scientifically engineered and replicated to create mycelium foams, and leather-like materials and composites, that can replace replenishable resources and environmentally harmful materials and products.

1.2.4 Fungi for colour and paper

An area of growing interest in the creative sector is the use of fungi for dyeing (Figure 4) and paper. Mushroom dyes which were initially used by indigenous cultures as war paints and early forms of makeup and cosmetics, have a long-standing tradition, which stems from the production of *'orchil'* and *'cudbear'* dyes from lichens (Spooner and Roberts, 2005).

Figure 4. Samples of fungi dyed wool – various species. © Author's archive.

Nowadays, a range of fungi species have been tested and described as an alternative to plant-based or chemical dyes, which can be used to dye fibres from plant and animal origin, as well as manmade protein materials. This is thanks to a global movement and an international community of mushroom dyers that began in Mendocino, CA in the 1960s with Miriam Rice (Jan 1918 – Aug 2010) who serendipitously discovered that a clump of Sulphur tufts gave a yellow dye. Rice went on to experiment with a range of fungal species and yarns, documenting the process and resulting colours, and passing the knowledge onto others via workshops and symposia (Johansson, 2016; Rice and Beebee, 1980; Rice and Beebee, 2007).

Using traditional methods of plant-based dyeing which rely on the use of mordants to (i) extract the pigment from the source, and (ii) bind the pigment to the fibre, fungi can yield a full spectrum of colour (Figure 5), and often times a range of different colours from the same fungus. For example, *Dermocybe phoenicea* var.

occidentalis, could give a range of pastel pinks, bright reds, browns and dark purples by regulating the pH using white vinegar and washing soda (Rice and Beebee, 2007).

Figure 5. Silk scarves dye project by the Scottish Fungi Dye Group[8]. Fungi dyes used: Cortinarius sanguineus (caps) – reds, Phaeolous schweinitzii + iron – soft greens / blue, Innonotus hispidus + iron – khaki greens, Phaeolous schweinitzii – yellow, Cortinarius semisanguineous (stalks) – peach, Innonotus hispidus – gold, Hapilopilus nidulans + ammonia – purples, Paxillus atromentosus, Paxillus atromentosus + iron – silver / dark greys. © The Scottish Fungi Dye Group

A known benefit of fungi dyes is the chitin content of the fungal cell wall, which yields dye results that are wash- and colour-fast, compared to some of the outcomes from plant-based dyeing.

Further applications, developed by members of the *International Fungi & Fibre Federation (IFFF)* include the use of fungi to extract pigments for watercolours and myco-stix™ (Johansson, 2016; Mushrooms for Color, 2017; Rice and Beebee, 2007), and to produce hand-crafted paper from trimitic polypores such as *Piptoporus betulinus*, *Fomitopsis pinicola*, *Fomes fomentarius, Trametes hirsuta, Trametes ochracea, Cerrena unicolor, Lenzites betulina, Daedalea quercina* and *Ganoderma applanatum* (Johansson, 2002; Johansson, 2016; Rice and Beebee, 2007). Much like the paper made from crustaceans, the paper derived from fungi is chitin-based and of high value. The paper colour would vary depending on the natural colour of the bracket, but could be modified during the making process,

[8] Members include: Marilyn Caddell, Patricia Gow, Marilyn Clark, Chris Simpson, Anna S King, Janette McKeown, Rita Barth, Gil Osirio, Joan Gale, Dee Crewdson, Ann Mulley and Jean Mounter

e.g., by using waste dye baths from the mushroom dyeing process. An additional benefit of making paper from fungi, is their high lignin content, as also noted by Hamlyn (1991), which means that the production of the paper does not require an additional binding agent, thereby not compromising the wholly natural composition of the paper.

Figure 6. Paper swatches produced from Piptoporus betulinus, Fomitopsis pinicola and Fomes fomentarius. © Johansson, 2002 (left) and Mushroom paper created from various species © Johansson, 2016 (right)

For the author, an engagement with the *International Fungi & Fibre Federation* through their biannual international symposium in Jaca, Spain in 2012, presented a rare opportunity to experience first-hand fungi dyeing, paper-making and watercolour painting processes (Ivanova, 2012a). Being part of a global community of artisans who carry a rich knowledge base of mycological science, chemistry, textile technology, spinning, weaving and dyeing, helped identify which fungi species would have the right properties for applications within the fashion and textiles domain (see further Section 1.4.1 'Material experimentation').

1.2.5 Fungi in textile technology – early experiments

In 1991, Dr Paul F Hamlyn and a group of scientists at the British Textile Technology Group (BTTG), were examining the roles of fungi in deteriorating textiles – a particular issue with the uniforms of troops fighting in tropical regions during World War II. Manmade materials were not popular at that time. This meant that uniforms were made of cotton, which easily degraded in hot and very humid conditions. This investigation into the roles of fungi in bio-deterioration of textiles, which in itself had significant implications for the protection of cultural heritage and artifacts (Breuker *et al.,* 2003; Hamlyn and McCarthy, 2000), led to a new line of enquiry looking at the potential beneficial applications of fungi in textiles – first published in Textile Technology International (Hamlyn, 1991).

The filamentous structure of fungal mycelium indicated the type of materials that could be produced, and the properties of fungi provided a rationale for the range of application. The novel cell wall chemistry, based on chitin suggested a potential use of fungal materials for wound dressings and medical textiles (Hamlyn and Schmidt, 1994). The fine filamentous structure indicated that microfungal nonwovens, or composite mats, could serve a range of applications requiring absorbent, binding, filtration and drug delivery properties. The speed of growth (biomass available in days), low-energy requirements and natural properties, pointed to market opportunities of varying scale and value, i.e., low value products such as absorbent materials, binding agents, filtration products; and high value products, e.g., artificial leather, metal-ion bisorption and would healing.

The fungal species that were tested by Hamlyn and his team included *Aspergillus oryzae*, *Mucor mucedo*, *Rhizomucor miehei* and *Phycomyces blakesleeanus*. Cultures were grown in bioreactors, resulting in a broth of very fine branched filaments which could be fabricated through wet-laying using standard laboratory paper-making equipment, either on their own, or mixed with conventional fibres, e.g., wood pulp or polyester. Alternatively, they could be freeze-dried to produce an absorbent pad of pure mycelium (Figure 7).

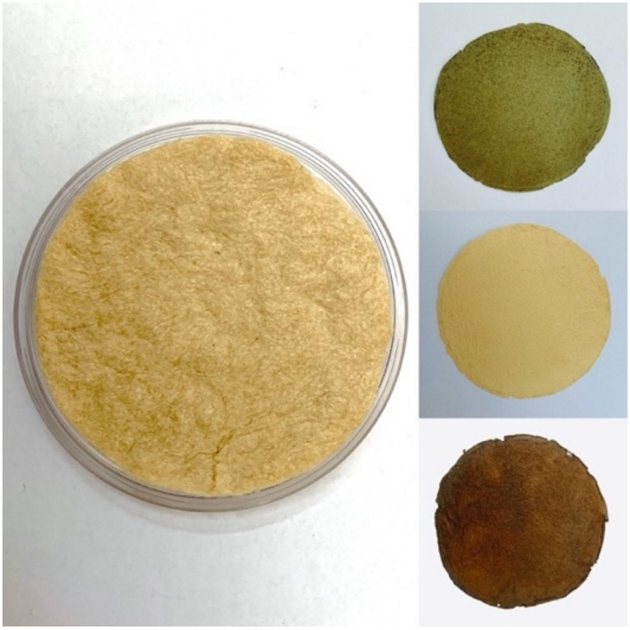

Figure 7. Absorbent mycelium pad (left) and paper swatches (right) gifted by Hamlyn to the author's collection. © Author's archive.

Further research by Hamlyn and Schmidt (1994) explored the potential therapeutic application of fungal filaments in medical textiles for wound dressing materials. Sadly, pursuit of commercial applications was considered futile at the time, due to patents existing in the area of chitin-based medical textiles (Ivanova, 2013a). However, in recent years, there has been a renewed interest and research in the use of fungi for high-performance paper-like materials, wound dressing materials, and water purification filters (Gandia *et al.,* 2021).

1.3 Fungi applications in contemporary design and bioconsumer products

Over the last decade we have seen a rapid growth in interest and developments in fungi materials across a variety of design applications. Foams and sheets grown from pure mycelium are being made into high-quality paper, textiles and leather-like materials. Biocomposites of mycelium grown on agroindustrial byproducts are finding commercial applications as packaging materials, insulation, building blocks, furniture and interior panels. Due to the beneficial properties of fungi, the scope for environmental impact through a new range of novel sustainable mycelium materials appears enormous: upcycling of byproducts and waste from other industries; a low-energy process associated with heterotrophic fungal growth; versatility of outputs; and biodegradability of the products at the end of their use. (Appels and Wösten, 2020; Camere and Karana, 2018; Gandia *et al.*, 2021; Karana *et al.*, 2018; Robertson *et al.*, 2020)

The following section provides an overview of leading fungi applications across domains and at various scales. This list is by no means exhaustive, but rather highlights key practitioners who have paved the way for widespread adoption of mycelium-based materials by designers, industry and consumers alike.

1.3.1 From building blocks to 'leather'

In the early 90s in San Francisco, artist Phil Ross began a creative practice inspired by the beauty, life cycle, medicinal properties and rich diversity in form, texture and colour of reishi mushrooms (MycoWorks, 2021). In 2008, his ongoing experiments in creating living sculptures from fungi, led to the inception of *'mycotecture'* – a term he used to describe the art of designing and building with fungi. The process was used to create strong, yet lightweight structures that could be deployed as building blocks to construct architectural frames, or alternatively moulded into domestic objects, e.g., chairs (Figure 8), by placing the live mycelium into a desirable shape. The work was exhibited internationally and earmarked fungi as a one-to-watch innovative and sustainable material.

Figure 8. 'Yamanaka Furniture' by Phil Ross (2012) as exhibited at Alive: New design frontiers (Collet, 2013) © Author's archive

In 2013, Philip Ross partnered with a long-term artistic collaborator – Sophia Wang – to found *MycoWorks*, where, together with a small team of creatives, they began to refine Ross' biotechnique into a patented *Fine Mycelium* technology. This entailed engineering mycelium during the growth phase to create dense, interlocking structures of filamentous growth. The technology was initially used for panels and moulded forms for interior and structural design, similarly to Ross' early works.

Soon after, in 2016, the team began to pursue a new application of this technology for flexible mycelium materials which would have the look and feel of bovine leather. *MycoWorks* assert that, in comparison with other 'mushroom leather' alternatives which are made of compressed mycelium foams[9], their *Fine Mycelium* technology allows them to engineer the desirable leather strength, performance and aesthetic properties during the mycelium growth phase. This offers a level of control over the finished products, to meet the required quality standards in the fashion and footwear industries.

In parallel, in Green Island (New York), *Ecovative* was founded in 2007 as a mycelium technology company to develop sustainable, biodegradable alternatives to styrofoam packaging and insulation materials (Ecovative, 2021). Their early products were based on a patented mycelium bonding technology, which exploited the natural properties of mycelium to self-assemble lignin and cellulose, in order to transform agricultural by-products, e.g., hemp hurd, into composite materials, which are now marketed under the brand *MycoComposite™*.

[9] Mycelium foams are typically produced via solid-state fermentation on pre-colonised ligno-cellulosic substrate, e.g., sawdust, whereby a thick foamy mycelium sheet is formed on the surface of shallow moulds, which is then harvested and compressed to decrease its thickness. See further: Gandia *et al.* (2021)

Today, *Mushroom® Packaging* is a separate branch of *Ecovative* and is licensed to companies across USA, Europe, the UK and Oceania. The mycelium technology itself has been further developed into a range of materials for applications in the built environment, and for consumer products ranging from high performance footwear, through leather alternatives, to skincare (Ecovative, 2021). The latter are based on two new technologies for flexible fungal materials: *MycoFlex™*, which according to Gandia *et al.* (2021), is the only commercially available pure mycelium foam; and *Forager™*, which uses an aerial mycelium farming technology to create sheets of the material that can be then processed by traditional tanneries into animal leather alternatives.

The most recent company to join the mycelium technology landscape across the Atlantic is *Bolt Threads*. *Bolt Threads* was founded in 2009 by a bioengineer, a biochemist and a biophysicist to develop biobased materials that counter the toxic processes, petroleum-based polymers and non-biodegradable materials of industries such as textiles and fashion. Following on from their first product, *Microsilk™* which was based on an advanced technology to mimic to production of spider silk, in 2018, *Bolt Threads* launched *Mylo™* (Figure 1, p.2) – a mycelium-based alternative to leather (Bolt Threads, 2021). *Mylo™* was first prototyped into fashion products by designer Stella McCartney through a recreation of her iconic *Falabella* bag, which was showcased for the first time at the *Fashioned from Nature* exhibit at the *Victoria & Albert Museum* in London (2018-2019).

The collaboration between *Bolt Threads* and Stella McCartney has set the blueprint for the following stages of development and market realisation of Mylo™ through international partnering and multidisciplinary working: with mushroom growers in the Netherlands using vertical farming to minimise ecological footprints; European leather tanneries to meet the aesthetic and performance requirements of traditional leather; and the fashion and sportswear industries who have the capability, resources and talent to bring mycelium-based products to market at scale.

What remains a key driver throughout the entire process of realisation is the sustainability imperative. Whilst the current *Mylo™* leather alternative is not fully plastic-free[10] and biodegradable, due to the processes involved in the material fabrication and finishing required to meet consumer expectations for softness, strength and suppleness. This level of transparency and attitude towards continuous improvement of the environmental impact of the process and finished product, paired with a realisation that *"a material's potential for impact depends on brand and consumer adoption, and a majority of consumers will not accept big*

[10] Mylo is currently certified as 50-85% bio-based https://boltthreads.com/technology/mylo/

sacrifices in quality compared to leather", highlights one of the main areas in the domain of mycelium-based consumer products that would require further attention, research and development.

1.3.2 The role and impact of a single designer

In parallel, Italian-born designer based in the Netherlands Maurizio Montalti, has led the introduction of fungi-based materials over the last decade in Europe and beyond. His Master's dissertation at Design Academy Eindhoven *'Continuous Bodies: cycles of decomposition triggering a symbiotic partnership between humans and fungi'* (Montalti, 2010a) considered the properties of fungi to decompose matter of both natural and synthetic origin. Through a series of material experiments and prototypes, Montalti began to probe a new domestic landscape of *'cultivated'* objects which would replace the environmentally harmful plastics (Montalti, 2010b; Montalto, 2010c).

The early works included various domestic objects which were *'grown'* into the desirable shape and form using moulds, by either utilising local waste, or by biodegrading existing polymeric materials. To describe his process of working with living mycelium, Montalti used the term *'growing design'*, which he compared to a method of *'slow'* 3D printing, whereby the speed of printing would correspond to the time needed for the fungi to grow (Montalti, 2014).

In Europe, Montalti's work, vision, and openness to collaborate and educate (Officina Corpuscoli, 2021) established a more versatile, wholistic and collaborative approach in the pursuit of fungal futures. This had important implications for the uptake and future development of fungi as a novel sustainable material, as well as inspiring and educating the next generation of biodesigners working with mycelium through extensive international lecturing and teaching practice[11].

A collaborative and inclusive approach pushing the boundaries of material properties and applications

In 2010 in Amsterdam, Montalti founded *Officina Corpuscoli* as one of the first design-led consultancies committed to studying and developing mycelium-based technologies. Through collaboration and co-creation with scientists and designers, Montalti not only explored the mechanisms underlying the structural and decorative properties of mycelium, but also

[11] Including positions as Head and Mentor for the MAD Master (Materialisation in Art and Design) at Sandberg Instituut, Associate Researcher at Design Academy Eindhoven, Artistic Director at dieDAS – Design Akademie Saaleck

identified opportunities for their improvement by assessing natural variations, environmental growth conditions, and genetic qualities of the selected mycelia. Pertinent examples of this include:

- *'The Future of Plastic'* exhibition (2014), which was commissioned by, and exhibited at the *Fondazione PLART* (Napoli). The show comprised a range of everyday objects which provoked the audience to rethink and reimagine the make-up of everyday environments (Figure 9);

Figure 9. 'The Future of Plastic' exhibition by Maurizio Montalti at Fondazione PLART in Napoli (Petroni, 2014) © Corpuscoli / Maurizio Montalti

- The collaboration with the Fungal group of the Utrecht University's Microbiology Lab and *Stichting Mediamatic* as part of the NWO-funded project *'Mycelium Design'* (2014 – 2015), which invited artists and designers to explore the wider material qualities and potential applications of fungi. This provided *Officina Corpuscoli* with multi-perspective feedback about design-led requirements for the properties and performance of mycelium materials for specific products and applications. The outcomes of this engagement were presented as part of the exhibition *'FUNGAL FUTURES / Growing Domestic Bio-Landscapes'* (2016). This inclusive and collaborative approach led to the development of novel material concepts, qualities, and design solutions (Figure 10);

Figure 10. Fungal Futures (Maurizio Montalti, 2016) © Officina Corpuscoli / Maurizio Montalti

- A commission by the *Museum of Modern Art (MoMA)* for the exhibition *'Items: Is Fashion Modern?'* (2017-2018) brought about a collaboration with Liz Ciokajlo (OurOwnsKIN) to create a mycelium-based prototype for a *MarsBoot*. This was as a design provocation to explore the evolution of our material culture in the 21st century, and specifically the values that drive the creation of new worlds. The fabrication process combined a range of hi-tech and low-tech processes to produce components of both pure and composite mycelium materials, with different physical and technical qualities (Figure 11).

Figure 11. Caskia / Growing a MarsBoot by Maurizio Montalti (Officina Corpuscoli) and Liz Ciokajlo (OurOwnsKIN). © George Ellsworth

Establishing a company that diversifies application

The range of material explorations, prototyping and collaborative effort, led to a realisation of the need to standardise and scale up mycelium technology, in order to realise the power and responsibility of design to create more sustainable materials and products that positively impact the industry and society at large. In 2015, together with project partners, Montalti founded *Mogu* in Inarzo (Northern Italy), to develop a range of mycelium-based composites and pure mycelium materials which would follow the principles of the circular economy (Mogu, 2021). The light, low density, strong, resistant, shock-absorbing, performative applications of fungi-based materials were translated into an ever expanding range of commercial applications such as flooring, acoustic interior panels (Figure 12), fashion and furniture.

Figure 12. Mogu – Radical by Nature – Acoustic Mycelium Panels. Photography by A.WORLD PRODUCTIONS © Mogu

1.3.3 Mycelium meets advanced technologies

Additive manufacturing, also referred to as 3D printing, has offered an alternative method for biofabrication, which Robertson *et al.* (2020) assert, could allow for the creation of previously unobtainable design morphologies, as well as extending the capability of 3D printing to provide an economically viable mass production method.

A pioneer in this space is Eric Klarenbeek, of design studio *Klarenbeek & Dros* (2021), who adapted a 3D-printer to print straw injected with mycelium. This method enables him to create strong, solid and lightweight structures with intricate detail. The work began in 2010 through a series of experiments developing cold paste extrusion-based mycelium printers. Later, several extruders were combined, to enable simultaneous printing with living mycelium and biopolymer scaffolding (FDM printing), to create more robust construction elements and larger structures. These resulted in the creation of a mycelium chair which used PLA scaffolding (Figure 13).

Figure 13. Mycelium chair made using an adapted 3D printing process by Eric Klarenbeek. © Klarenbeek & Dros

However, the early prototypes revealed a limitation of the existing biopolymers used in 3D printing, which were not the optimal growth media for mycelium. This resulted in further research and development using algae- and seaweed-based biopolymers, to improve the technology, extrusion methods and suitability for specific strains of fungi, to enhance the speed of growth, and the strength and overall properties of the final designs (Figure 14).

Figure 14. Mycelium chair made using the improved 3D printing process, exhibited at the Centre Pompidu, Paris (2019). © Klarenbeek & Dros

The improved method also delineated wider applications within architecture. A collaboration with *Biobased Creations* of Dutch design company *New Heroes* and *Dutch Design Foundation,* led to the creation of a fully biobased installation – *'The Growing Pavilion'* (2019), which formed part of *Dutch Design Week 2019*.

The advancement of mycelium technologies, the collaborative and interdisciplinary efforts to refine material properties, the alignment with the sustainability agenda, and the scaling up of production and commercialisation, have shifted the design discourse over the last ten years – from a *'what if?'* space probing a future where our material world and everyday environments would be made of mushrooms, through the excitement of having a new medium and a new process to *'grow'* design, to a space where consumer engagement and uptake, aesthetic and performance properties, and a wholistic narrative between material properties, application and sustainability, are becoming the key focus of design attention and further development.

The latter question, about how we normalise novel, yet obscure materials from fungi, has been the focal point for the author's design investigation into the use of fungi for bio-based materials and products. The following section provides a personal narrative of the activities and key considerations in developing mycelium-based textiles and domestic objects.

1.4 A design-led case study: the role of human engagement

A starting point for the enquiry was the Russian documentary film *'Плесень' ('Mould')* by Dmitry Vassilev's (2009), which explored the roles fungi play for life on Earth, from fungal diseases caused by *Aspergillus niger*, to beneficial uses such as antibiotics through the discovery of penicillin:

> *"It first appeared on Earth 200 million years ago. It kills and saves lives. It is often called the "devil's bread" and "God's spit". We don't even think what ancient secrets and hidden powers might be concealed in this cursed and blessed phenomenon… mold." (Vassilev, 2009)*

In 2010, when the applications of fungi in design described above where still in their infancy, the film provoked thinking about the potential role of design in communicating the useful properties and value of fungi, to counter negative association of fungi with mould, decay, disease and deterioration[12], which may have been a reason for the initially slow uptake of fungi in the newly emerging field of biofabricated design.

Psychologically, the popular association of fungi with mould brings about a behaviour of disease-avoidance. It is related both to our evolutionary past and the fear of contamination, which Rachman (2004) describes as *"an intense and*

[12] Attitudes, perception and use of fungi can vary dramatically across cultures (Rolfe and Rolfe, 1925).

persistent feeling of having been polluted or infected or endangered as a result of contact, direct or indirect, with a person / place / object that is perceived to be soiled, impure, infectious or harmful…". This perceived state evokes emotions such as disgust and impurity, which are usually influenced by visual and olfactory stimuli that can be produced by decaying matter (Figure 15).

Figure 15. Aversion response to moulded fruit, expressed by a workshop participant (Kingston School of Art, 2012). © Ezzidin Alwan

The film inspired a year-long design investigation for a Master's project in Fashion at Kingston School of Art (Ivanova, 2011). The project explored how, through careful crafting of design and aesthetic properties, we could (i) overcome negative associations of fungi to propose applications within the fashion domain, and (ii) educate the public about the importance and value of fungi to humankind. This involved a series of experiments with mould growth on textiles and paper, which were conducted with support from Professor Lory Snyder from the School of Life Sciences, Pharmacy, and Chemistry at Kingston University London.

Through the use of macro photography (Figure 16), the beauty of microscopic moulds formed the basis for a garment collection that explored the potential value of fungi within sustainable fashion. Different textiles techniques, including digital printing on silk chiffon, flocking and laser cutting, were then used to translate the narrative into garment designs (Figure 17). The collection also included several pieces with living moulds, encapsulated within sealed PVC components of the dress, to provoke audience engagement with the idea of wearing clothing made from, or still containing, living organisms.

In the context of fashion, where there exists a very immediate, intimate and sensorial relationship between the human body and the garment, it appears imperative to consider how we introduce novel bio-based materials from fungi. This formed the basis for a doctoral design research investigation, which aimed to advance engagement and perception of fungi, alongside any further developments in the chain of market realisation (Ivanova, 2015).

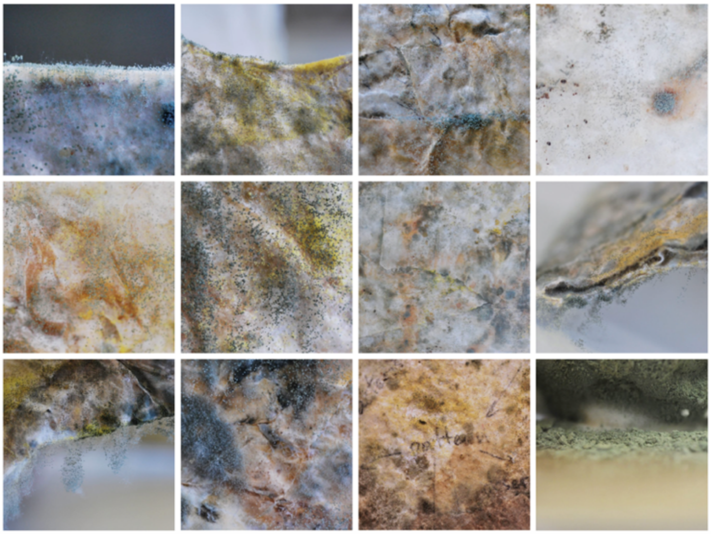

Figure 16. Mould growth on paper and textiles. © Author's archive

Figure 17. Garment designs inspired by mould, showcased at Vauxhall Fashion Scout (Freemasons' Hall London, Sept 2011). © Ezzidin Alwan

The review of science literature and contemporary design practice – some of which is covered in the previous sections of this chapter – provided a starting point for the author's investigation in the use of fungi to fabricate textile-like structures. Preliminary questions that formed the basis for this investigation centred on identifying which fungal species would be best suited to fabricate soft, yet structurally sound materials. The design process was open ended, to allow for material forms and design applications to emerge organically from the natural properties of fungi. An early realisation was the need for partnering and interdisciplinary work, to advance both the fabrication and the uptake of mycelium-based materials.

Answering the above questions entailed a simultaneous pursuit of collaborations with scientists and the development of a design-led methodology to test engagement with fungi in the context of fashion.

1.4.1 Material experimentation

Early on in the research process, it became apparent that attempting to 'grow' a material in the design studio, without scientific input and technology, would lead to outcomes with many limitations. Support was therefore sought from several scientists across the UK who provided invaluable guidance, feedback and training, as well as access to resources and facilities.

Dr Paul F Hamlyn from the British Textile Technology Group, who had pioneered research on the use of fungi for medical textiles as described earlier in this chapter (Hamlyn, 1991; Hamlyn and Schmidt, 1994) was interviewed to understand the possibilities of using existing textile technologies in working with fungi, as well as some of the early limitations of fabricating textile forms (Ivanova, 2013a).

Prof Lynne Boddy, MBE FRSB FLSW, Professor of Microbial Ecology at Cardiff University, who leads research on the ecology of wood decomposition, helped identify cord-forming fungi as the preferred species for material fabrication (Ivanova, 2013b). In nature, these fungi form cords with strong tensile properties in their search for new food sources and interaction with other microorganisms in the soil (Figure 18).

Figure 18. Cord-forming fungi at the laboratory of Professor Lynne Boddy, Cardiff University. Images taken by the author with permission, 2013

Dr Bryn Dentinger, Dr Begona Aguirre-Hudson and Dr Heidi Doring – mycologists at the Fungarium at the Royal Botanic Gardens Kew (Ivanova, 2012b) – enabled early experiments to be conducted by providing space, resources and in-kind support for the research.

From the above, it appeared possible to imagine that, depending on the morphology of the fungal mycelium and the type of growth media and process, we could fabricate a variety of textile-like structures, e.g., a mycelium cord, a felt-like fungal mat, a membrane, or a lace-like structure. These could be either conventionally fabricated by appropriating existing textile technologies, or grown as bio-films using existing biodesign and biotechnology methods.

This led to series of experiments, conducted at Cardiff University and the Royal Botanic Gardens Kew, aimed at testing the potential of different fungal species to create textile-like structures on their own, and as composite materials with fabrics. Some of the early outcomes (Figure 19) explored the behaviour and properties of various species in response to traditional textiles, e.g., linen, silk and netting. It was observed that some fungi develop stronger, cord-like mycelium when grown on protein-based textile materials, particularly net-like and open weave fabrics.

Figure 19. Mycelial textile structures on netting and open weave cotton fabric. © Author's archive, 2013

1.4.2 Advancing engagement and perception

In parallel, another experiment conducted with Dr Simon Park from the University of Surrey explored the potential of cheese-moulds such as *Penicillium roqueforti* and *Penicillium camemberti* to form textile-like biofilms when cultured on milk (Figure 20). The resulting materials had the appearance of suede and demonstrated both anti-bacterial and water-repelling properties (Figure 21).

Figure 20. MycoCouture: cultured form P. roqueforti and P. camemberti (Park and Ivanova, 2013). Image courtesy of Dr Simon Park, 2013

Figure 21. Close up of the MycoCouture surface showing its hydrophobic properties (Park and Ivanova, 2013). Image courtesy of Dr Simon Park, 2013

These early experiments began to outline some of the benefits of bio-based materials. For example, 'living garments' could provide a route for re-introducing and re-engaging with specific micro-organisms into our everyday, with a view to re-balancing our environment and relationship with nature, and potentially improving health and wellbeing[13].

However, if this scenario were to be realised in manufacturing, a pertinent question that would arise would be about how a high-street brand would engage with the complex challenges of selling such a concept to the consumer. Mould, to be converted into a durable material, would face the challenge of overturning its inherent negative associations with decay, disease and deterioration. Shifting this perception would be necessary in order for the material to succeed in a market place that increasingly demands transparency of material sourcing, production,

[13] Some scientists postulate that the move towards an increasingly hygiene-monitored urban environment, could be a likely cause for some contemporary autoimmune and idiopathic diseases (Dunn, 2011; McKenna, 1992).

and heightened aesthetic awareness from consumers (Fletcher, 2008; Fletcher and Grose, 2012).

History provides a pertinent example of the challenging and lengthy process of introducing technical and material inventions to wider fashion and textile markets. At the turn of the twentieth century, an alliance between the three global industries of chemistry, textiles and fashion succeeded in synthesising the first man-made material, viscose rayon, produced from chemically pulped-down wood (Handley, 1999). Over the following decades studies of polymerisation in natural fibres, led to the invention of nylon by *DuPont* in the 1930s (DuPont, 2014).

Nylon was introduced to potential markets in 1939, as part of *DuPont*'s *Children of Science* exhibition at New York World's Fair, under the slogan *'better things for better living'* (Handley, 1999). The initial promise from science behind this new material was affordable luxury, as an alternative to the relatively more expensive silk. Ultimately, significant time and effort in branding and promoting the new *'beauty fibres'* was required *"in order to convince users and consumers that synthetics were as 'good' and 'luxurious' as silk"* (Handley, 1999). Generic man-made textiles, e.g., viscose, acetate, polyamide, polyester and acrylic, were translated into brand names arising from blends of these materials such as *'Dacron', 'Terylene', 'Trelenka', Crimplene', 'Orlon', 'Courtelle', 'Tactel', 'Tencel'*, etc.

However, early synthetic fabrics and their marketing as *'artificial silk'* did not meet consumer expectations, and evoked a negative public perception bound by the *"artificiality, and counterfeiting of the authentic",* as stated in a report commissioned by DuPont in 1927:

> *"DuPont had realised that selling a new material meant selling an abstract concept, which relied on associations with comfort, performance, economy and luxury." (Handley, 1999)*

The story of nylon serves as an example of a timeline of the market assimilation process of novel materials, related terminology, and an urgent requirement for a shift in societal perception and attitudes. Negative perception of synthetics and how they were publicly received, was fuelled by the popular perception of science as *'unnatural'* at the time, and was further exacerbated by the poor tactile, visual and behavioural qualities of the early synthetic materials. It took decades of fashion designers, namely the French couture houses, to develop the potential of synthetic materials, and, *"deep within the collective psyche still lingers a suspicion, if not a prejudice, against the words 'plastic' and 'synthetic'."* (Handley, 1999)

With hindsight, a more wholistic or a stakeholder approach by the design, science and engineering sectors, with due consideration of all human, material and sensory factors, would have led to a speedier and more fluent integration of synthetic materials on the marketplace.

From the above, the further development of mycelium-based materials by the author, focused on the presentation and education of audience groups via workshops, design probes, seminars and exhibitions (Figure 22), to best present the advantages and disadvantages of newly developing materials, to make them socially acceptable and desirable (Ivanova, 2015). An inclusive approach, which invites stakeholders, e.g., end-users and consumers (Eikhaug and Gheerawo, 2010; Saunders and Stappers, 2008; Suri, 2007), to engage with novel and challenging material concepts and related experience at the early stages of their development, was considered invaluable to inform the design process, and ensure the desirability and market viability of such concepts.

Figure 22. 'Mouldy' T-shirts: design probes co-created with research participants, PhD Design Research exhibition, November 2012, Kingston University London. © Author's archive

1.4.3 Design collaboration

The potential challenges associated with human engagement and perception with fungi applications for clothing, e.g., questions related to allergies, health and safety, but also concerns about the need to evolve performance and durability – which would require a lengthy process of refinement of material properties and product functionality – led to a consideration of where fungi-based materials may find a more natural, psychologically comfortable, and easy-to-integrate application. This speaks to a bigger vision for designing a material world, environments and objects in a sensitive and sensible way, wherein conscious decision and choice of raw material, processes, design aesthetic, function and presentation becomes a holistic narrative, but also a compass for design production and integrity.

In 2016, the author met Sebastian and Brogan Cox of furniture design company Sebastian Cox Ltd. (Cox, 2017) who were looking to explore the naturally occurring relationship between fungi and wood through the design of domestic objects and furniture. The project was driven by a shared vision of made objects, created in a rational way, with complete alignment and integrity between choice of materials, design process, aesthetic, outcome and application. Through a combined expertise in mycelium, wood and design, the team pursued the development of a furniture collection that would evolve material culture in the context of sustainability and biodiversity, and positively impact the way people choose the objects in their home.

There were several key considerations:

Purpose

The project was initially inspired by an image of two tree branches that were bound together by the black fruitbody of an unidentified polypore, which Sebastian took on one of his trips to the woods in Kent. This suggested a potential application of mycelium as a natural alternative to the glues used in engineered wood products.

> *"In our workshop we don't use composite wood materials because I've never been quite satisfied with the binding agent holding the wood together […] As a result, I've always had a kind of fantasy interest in 'reinventing' a type of MDF and finding new ways to bind wood fibres into either sheets or mounded forms, ideally without glue."*
> *(Sebastian Cox in Frearson, 2020)*

This image became symbolic of the overarching ethos and purpose of the collaboration, which was later named *Mycelium + Timber* (2017). The vision for *Mycelium + Timber* focused on the marriage of the naturally occurring properties of fungi with existing carpentry processes and techniques, to create domestic objects that equally celebrate fungi and wood, rather than solely using woodchip waste from the studio mill as a substrate for a composite material.

Species

The team embarked on a series of experiments, set up in a purpose-built lab in the Cox' workshop, which aimed to identify the right match between fungal species and the hardwoods that the studio worked with, to utilise the (waste) resource that was available in the best possible way.

An imperative was to work with locally sourced wood, e.g., birch, ash, sycamore and chestnut, in line with the overarching sustainability narrative of the collection, and in alignment with the ethos of Sebastian Cox Ltd. In addition to the by-products of the workshop's milling and furniture making processes, the team hoped to find a fungus that would grow well on green coppiced hazel (*Corylus avellana*) and goat willow (*Salix caprea*). Goat willow grows in abundance, which presents a challenge to woodland management, but has little economic value and is often considered waste.

Fungal species were selected based on their wood-decaying properties, their ability to grow in culture and their speed of growth, as well as the above guiding principle of being local to the South-East of England. It was considered important that the fungi were safe to use, i.e., with known medicinal, food or other ethnomycological applications, to overcome any future potential challenges with health and safety, or perception.

Process

An imperative was to learn from, and work with the living material, which was realised through an extensive review of literature at the *Fungarium* at the *Royal Botanic Gardens Kew*, and a series of experiments. *Fomes fomentarius* emerged as the most suitable species that worked effectively with coppiced hazel and goat willow (Figure 23).

Figure 23. Petri dish with Fomes fomentarius grown onto wood shavings. © Petr Krejci

The process entailed growing grain culture of *Fomes fomentarius* on sterilised greed wood waste (1.5h at 60°C) for two weeks, after which time the composite material could be moulded to shape (Figure 24), and let to grow for a further two weeks to take up the desirable form. As previously discussed, this process has no extreme requirements for ambient temperature, humidity or light. Once the growing process is complete, the finished artefacts are kiln-dried to remove moisture and terminate any further growth.

Figure 24. Preparation of light shade formers filled with 'myceliated' wood for a second growth phase. © Petr Krejci

Properties

Some of the key observations about the behaviour and properties of mycelium that were considered in the design development and pursuit of applications included:

- Changes in colour, texture, and material properties due to variation in growing and environmental conditions;
- Ability of the mycelium to take up both the shape and surface properties of the mould within which it is grown;
- The binding properties of mycelium, which indicated applications for seamless joining of different furniture components;
- The lightness of the composite material which suggested applications for domestic objects that are not weight bearing, unless reinforced with integrated wooden structures;

- The spongelike natural give of the pure mycelium foam, which formed as a top layer in culture vats or moulds, and in turn indicated a suitable application for cushioning and insulation (Figure 25);

- Sensorial properties including a pleasant, woody or earthy smell, and soft-to-touch velvety texture;

- Hydrophobic and fire-retardant properties.

Figure 25. A cross-section of moulded component illustrating different properties of the composite material. © Author's archive

Outcomes

The above properties guided the creation of prototypes for two domestic objects: a ceiling pendant in two different sizes, and a stool. These were considered the most appropriate applications that would work well with the natural properties of mycelium, as opposed to trying to enforce a particular shape or design. Further considerations included how to achieve a desired aesthetic without the need for extensive human labour, or the employment of additional hi-tech processes, which would not sit well with the overall sustainability narrative.

The ceiling pendants (Figure 26) were grown within reusable moulds in the shape of a witch's hat. A hand-turned wooden rose and a woven rim were integrated in the design to translate the natural relationship between fungi and wood into lightweight, incredibly strong and completely compostable pieces of design. A similar process, of growing mycelium around a purpose-made wooden frame were used to create the stool, whereby the stool itself became the mould for the mycelium growth (Figure 27).

Figure 26. Ceiling pendants made using green wood waste bound by mycelium. © Petr Krejci

Figure 27. Two mycelium stools made using green wood waste bound with mycelium to a wooden base and legs. © Petr Krejci

Presentation

The presentation of these early prototypes was a carefully considered process to introduce the collection in a way that would normalise fungi-derived products for applications in the home. *Mycelium + Timber* was first displayed during *London Design Festival 2017* as part of the *Design Frontiers* exhibition at Somerset House. The domestic environment of Somerset House – with its wooden floors, fireplace and large windows (Figure 28) – was opportune, to allow the audience to engage with, and imagine, what it would feel like to own, and care for, mycelium furniture and domestic objects; a departure from their presentation within a gallery or museum context.

Figure 28. Mycelium + Timber display at London Design Festival 2017, Design Frontiers, Somerset House. Image courtesy of London Design Festival. © Ed Reeve

The installation presented the research and creative process – from the raw materials to the finished prototypes – to illustrate the translation of the remarkable and ancient material relationship between wood and fungi into strong, lightweight and entirely compostable forms that can be applied to furniture design through the use of previously overlooked materials. Visitors were able to touch the objects on display, feel their velvety texture, and even smell them if they so wished (Figure 29).

The transparency of the production process, including objects being 'grown' for the duration of the exhibition, captured the audience imagination, with many questions ensuing about other potential applications and the evolution of the aesthetic properties. Overall, the exhibition was successful in fulfilling its intention to take mycelium-based products out of the lab, or the gallery space, and into a collective appreciation of their value and applications withing the home.

Figure 29. Audience engagement with Mycelium + Timber artefacts during London Design Festival 2017. Design Frontiers, Somerset House © Author's archive

1.5 Conclusion and future vision

This chapter set out to trace the value and applications of fungi within the domain of design for bioconsumer products. The natural properties of fungi, linked directly to their role within the Earth's ecosystem, have delineated multiple beneficial uses, which biotechnology is converting into commercial applications. In this space, several roles have emerged for design and designers in the entire chain of market realisation.

Future casting

Innate to design thinking is the ability to imagine new futures and applications, beyond what is currently scientifically feasible, or viable in relation to the market. Through design methods, e.g., speculative prototypes, design probes, concept drawings and moving image, designers are able to map and visualise the scenarios and systems that would be required to realise mycelium products, as well as raising questions about the wider implications, ethics, and responsible creation of new material futures. A pertinent example here was the *Caskia* MarsBoot by Montalti and Ciokajlo (Section 1.3.2).

Probing and prototyping

Unlike other material revolutions, such as the invention of synthetics which was referenced above (Section 1.4.2), the development of mycelium-based materials for design applications has been largely championed by artists, designers and design entrepreneurs, e.g., Franklin, Ross, Montalti and Klarenbeek. A curiosity to explore new fabrication processes and media, through design experimentation and interdisciplinary collaborations, have enabled creatives to prototype early forms and applications for fungi in design.

Design-mindedness

Design-mindedness speaks to the ability of designers to think holistically about purpose (need), application, functionality, fabrication, aesthetic and audience engagement and impact, in the development of new market propositions. In the case of fungi, which may bring about negative associations with mould, mildew, decay and rot, it has been imperative to consider how we educate, evolve perception, and normalise mycelium products, in parallel with scientific developments and research to bring such products to market.

Craft and narrative

Working with the natural properties of select fungal species, building on traditional craft and making techniques, and introducing advanced technologies, e.g., 3D printing, has enabled designers to advance the material aesthetic, design narrative, and applications for fungi in design. In that, sustainability becomes more than a rationale for the development of mycelium products, but rather an integrity of thought and practice about *how* these products are being brought to market (as evidenced by the Cox and Ivanova case study presented in Section 1.4.3)

Commercialisation

Over the last decade, design-science-industry partnerships, e.g., *MycoWorks, Ecovative*, *Officina Corpuscoli*, *Mogu* and *Bolt Threads*, have attracted funds, talent, stakeholders and resources, to refine mycelium technologies and scale up materials and products for applications as wide as packaging, insulation, flooring, acoustic panels, apparel and cosmetics amongst others. In this space, the role of design is to lead creatively, and push the boundaries of the visual and material language being developed around these new products[14]. In fashion in particular, where there exists an intimate relationship between the garment and the human body, leaders in the fashion and sportswear industries have begun to introduce concept artefacts that recreate their iconic designs within fungi-derived materials, e.g., adidas' *Stan Smith Mylo™* shoe and Stella McCartney's *Falabella* bag, to make mycelium materials accessible to the wider consumer.

The next stage of development for fungi-based applications in design, is concerned with overcoming current limitations related to scalability and the processing of finished products, to meet the demands of performance and aesthetic as expected of conventional consumer goods. At present, the introduction of additives and finishing agents, e.g., through the use of traditional tanning processes in the production of mushroom 'leather', limits the biodegradability of the final outcomes (Material Innovation Initiative, 2020). In the first instance, other natural substances and compounds could be developed to improve the sustainability markers of some mycelium composites; a specific example being the use of fungi as dyes themselves, which is still a commercially underexplored resource. Ultimately, with the advancement of science, desirable properties could be engineered and pre-programmed at the growth phase.

Furthermore, in relation to advancing scalability and market uptake, one approach that has not been fully considered in the context of fungi-derived materials yet, is that of inclusive design. The tools of inclusive design – traditionally employed to include the needs and requirements of people who are excluded from mainstream design consideration based on ability, age and other demographic factors (Eikhaug and Gheerawo, 2010) – could be deployed in this new context, to advance the sensory properties of mycelium materials, scope new applications, and diversify business models. An inclusive design approach would help realise a mycelium-

[14] Beyond the examples of practice referenced in this chapter, designers and design studios who are advancing the applications, material and sensory properties of mycelium-based products include: Valentina Dipietro, Biohm and Mycelium Tectonics (product design and architecture); blast.studio (3D printing); Mycotech Lab, Aniela Hoitink and Kristel Peters (fashion) amongst others.

based future with long-term sustainability in achieving planetary, societal and economic impact.

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References

adidas (2021) *Stan Smith Mylo™: made using mushrooms.* Available at: https://www.adidas.co.uk/blog/663481 (Accessed: 4 July 2021).

Antonelli, A., Smith, R.J. and Simmonds, M.S.J (2019) ‘Unlocking the properties of plants and fungi for sustainable development’, *Nature Plants, (5),* pp. 1100–1102.

Appels, F. VW and Wösten, H. AB (2020) Mycelium Materials. *Encyclopedia of Mycology, 2*, pp. 710-718.

Boddy, L. (2013) ‘Fungi - the most important organisms on the planet?’ at *2008 Earthwatch debate*. Available at: http://www.cardiff.ac.uk/biosi/resources/web%20EW%20Fungi.mov (Accessed: 12 August 2014).

Boddy, L. and Coleman, M. (eds.) (2010) *From Another Kingdom: The Amazing World of Fungi*. Edinburgh: Royal Botanic Gardens, Edinburgh.

Bolt Threads (2021) *Bolt technology – meet Mylo™*. Available at: https://boltthreads.com/technology/mylo/ (Accessed: 4 July 2021).

Breuker, M., McNamara, C., Young, L., Perry, T., Young, A. and Mitchell, R. (2003) 'Fungal growth on synthetic cloth from Apollo spacesuits', *Annals of Microbiology, 53*, pp. 47-54.

Butu, A., Rodino, S., Miu, B. and Butu, M. (2020). ‘Mycelium-based materials for the ecodesign of bioeconomy’. *Digest Journal of Nanomaterials and Biostructures, 15,* pp. 1129-1140.

Camere, S. and Karana, E. (2018) ‘Fabricating materials from living organisms: An emerging design practice’, *Journal of Cleaner Production, (186*), pp. 570-584.

Catts, O., and Zurr, I. (2004) *Victimless leather - a prototype of stitch-less jacket grown in a technoscientific "body"*. Available at: http://www.tca.uwa.edu.au/vl/vl.html. (Accessed: 4 July 2021).

Charaya M.U. and Mehrotra R.S. (1999) ‘From Ethnomycology to Fungal Biotechnology: A Historical Perspective’. In: Singh J. and Aneja K.R. (eds.) *From Ethnomycology to Fungal Biotechnology*. Boston, MA: Springer.

Collet, C. (2012). BioLace: An exploration of the potential of synthetic biology and living technology for future textiles. *Studies in Material Thinking, 7*

Collet, C. (2013). *Alive: New design frontiers.* Available at: http://thisisalive.com/ (Accessed: 10 July 2021).

Congdon, A. (2014) *Amy Congdon: Biological Atelier.* Available at: http://www.amycongdon.com/ (Accessed: 30 July 2014).

Cooke, R. C. (1977) *Fungi, man, and his environment.* New York: Longman.

Corbman, B. P. (1985) *Textiles: Fiber to Fabric. 6th edn.* Singapore: McGraw-Hill Book Co.

Cox, S. (2017) Mycelium + Timber: Exploring biofacture in a new collection of grown furniture. Available at: https://www.sebastiancox.co.uk/news/mycelium-timber-exploring-biofacture-in-a-new-collection-of-grown-furniture (Accessed: 11 July 2021).

Deshmukh, S. K. and Rai, M. K. (eds.) (2005*) Biodiversity of Fungi: Their Role in Human Life*. Enfield: Science Publishers.

Dugan, F. M. (2011). *Conspectus of world ethnomycology: Fungi in ceremonies, crafts, diets, medicines and myths.* St. Paul, Minn.: APS Press.

Dunn, R. (2011) *The Wild Life of Our Bodies: Predators, Parasites, and Partners That Shape Who We Are Today.* New York: HarperCollins.

DuPont (2014) *Innovation Starts: 1939 Nylon.* Available at: http://www2.dupont.com/Phoenix_Heritage/en_US/1939_c_detail.html (Accessed: 26 April 2014).

Ecovative (2021) *Ecovative Design: We Grow Materials.* Available at: https://ecovativedesign.com (Accessed: 10 July 2021).

Eikhaug, O. and Gheerawo, R. (eds.) (2010) *Innovating with People: the business of inclusive design.* Oslo: Norwegian Design Council.

Fashioned from Nature (2018-2019) [Exhibition]. Victoria & Albert Museum, London. 21 April 2018 – 27 January 2019

Fletcher, K. (2008) Su*stainable fashion and textiles: design journeys.* London: Earthscan.

Fletcher, K. and Grose, L. (2012) *Fashion & sustainability: design for change.* London: Laurence King.

Forgacs, A. (2013) *Leather and meat without killing animals.* TED. Available at: https://www.ted.com/talks/andras_forgacs_leather_and_meat_without_killing_animals?language=en (Accessed: 4 July 2021).

Franklin, D. M. (2004) *Fibre Reactive a Living Garment. A Synergy of Biological Technology and Art*. Masters of Arts Dissertation, The School of Contemporary Arts, Faculty of Communication and Creative Industries, Edith Cowan University.

Franklin, D., and Cass, G. (2014) *Micro'be' fermented fashion.* Available at: http://bioalloy.org/images/projects/microbe/micro_be_technet_paper.pdf (Accessed: 20 January 2015).

Frearson, A. (2017) Mushroom mycelium used to create suede-like furniture by Sebastian Cox and Ninela Ivanova. Available at: https://www.dezeen.com/2017/09/20/mushroom-mycelium-timber-suede-like-furniture-sebastian-cox-ninela-ivanova-london-design-festival/ (Accessed 11 July 2021).

FUNGAL FUTURES / Growing Domestic Bio-Landscapes (2016) [Exhibition]. 24 March – 16 May 2016. Available at: https://www.corpuscoli.com/projects/fungal-futures/ (Accessed: 10 July 2021)

Gandia, A., van den Brandhof, J. G., Appels, F. V. W. and Jones, M. P. (2021) 'Flexible Fungal Materials: Shaping the Future', *Trends in Biotechnology, 2060*, pp.1-11.

Ginsberg, A. and King, J. (2009-2011) *E.chromi.* Available at: http://www.echromi.com/ (Accessed: 20 January 2015).

Hallett, C. and Johnston, A. (2010) *Fabric for Fashion.* London: Laurence King Publishing Ltd.

Hamlyn, P. F. (1991) 'Fabricating fungi', *Textile Technology International*, pp. 254-257.

Hamlyn, P. F. and McCarthy, B. J. (2000) 'Talking rot...and mildew on textiles', *Biologist, 4* (47), pp. 194-196.

Hamlyn, P. F. and Schmidt, R. J. (1994) 'Potential therapeutic application of fungal filaments in wound management', *Mycologist, 8 (4)*, pp. 147-152.

Handley, S. (1999). *Nylon: The manmade fashion revolution.* London: Bloomsbury.

Harding, P. (2008) *Mushroom Miscellany.* London: Collins

Items: Is Fashion Modern?' (2017-2018) [Exhibition]. Museum of Modern Art (MoMA), New York. 1 October 2017 – 28 January 2018.

Ivanova, N. (2011) *Moulded Mind.* Available at: http://mouldedmind.blogspot.com/p/moulded-mind.html (Accessed: 10 July 2021).

Ivanova, N. (2012a) *12th International Fungi & Fibre Symposium.* Unpublished Report.
Ivanova, N. (2012b) *The Fungarium.* Unpublished Report.
Ivanova, N. (2013a) *Interview with Dr Paul F Hamlyn.* Unpublished Report.
Ivanova, N. (2013b) *Visit to Cardiff University with Prof Lynne Boddy.* Unpublished Report.
Ivanova, N. (2013c) 'The human-mould-fashion relationship: fungi applications for future design scenarios in fashion and textiles fabrication'. In *Futurescan 2: Collective voices.* Sheffield Hallam University, 10-11 January 2013. Association of Fashion and Textiles Courses, pp. 34-41
Ivanova, N. (2015) *The T-Probe: A fashion-led approach to advance understanding of novel and challenging materials concepts and sensory experiences.* PhD Thesis, Kingston University London.
Johansson, L. (2002) *Mushroom Paper: Instruction for your own production using Piptoporus betulinus, Fomitopsis pinicola, Fomes fomentarius.* Sweden: Liza Johansson
Johansson, L. (2016) *Pigment & papper av svamp.* Sweden:Vulkan
Karana, E., Blauwhoff, D., Hultink, E. and Camere, S. (2018) When the Material Grows: A case study on designing (with) mycelium-based materials. *International Journal of Design, 12(2),* pp.119-136.
Kendall, B. (2013) *The Hidden Kingdom of Fungi*. Radio 4: BBC.
Klarenbeek, E. and Dros, M. (2021) Klarenbeek & Dros: Designers of the Unusual. Available at: https://www.dotunusual.com (Accessed: 11 July 2021)
Lee, S. (2005) *Fashioning the future: tomorrow's wardrobe.* London: Thames & Hudson.
Lee, S. (2011) *Grow your own clothes*. TED. Available at: https://www.ted.com/talks/suzanne_lee_grow_your_own_clothes?language=en (Accessed: 20 January 2015).
Lee, S. (2012) 'Biocouture or How to Grow a Frock...', in Hemmings, J. (ed.) *The Textile Reader*. London: Berg, pp. 391-394.
Lee, S., Congdon, A., Parker, G. and Borst, C. (2020). Understanding "Bio" Material Innovations: a primer for the fashion industry. Biofabricate and Fashion for Good. https://app.box.com/s/amjq9anszv8hvwdexoxg6wubes4aaxqa
Material Innovation Initiative (2020) *Technology assessment: mycelium leather.* Available at: https://www.materialinnovation.org/reports (Accessed: 11 July 2021)
McKenna, T. K. (1992) *Food of the gods: the search for the original tree of knowledge: a radical history of plants, drugs and human evolution.* London: Rider.
Meyer, V., Basenko, E.Y., Benz, J.P. *et al.* (2020) 'Growing a circular economy with fungal biotechnology: a white paper'. *Fungal Biology and Biotechnology, 7 (5*), pp. 1-23
Mogu (2021) *Radical by Nature.* Available at: https://mogu.bio (Accessed: 10 July 2021).
Montalti, M. (2010a) *Continuous Bodies: Cycles of Decomposition Triggering a Symbiotic Partnership Between Humans and Fungi.* MA thesis. Design Academy Eindhoven.
Montalti, M. (2010b) *Continuous bodies – Bodies of Change.* Available at: https://www.corpuscoli.com/projects/bodies-of-change/ (Accessed: 4 July 2021).
Montalti, M. (2010c) *The Growing Lab.* Available at: http://www.corpuscoli.com/projects/the-growing-lab/. (Accessed: 4 July 2021).
Montalti, M. (2014). *The future of plastic.* Retrieved from http://www.corpuscoli.com/projects/the-future-of-plastic/
Moss, M. O. (1987) 'Fungal Biotechnology Roundup', *Mycologist, 21 (2),* pp. 1-58.
Mushrooms for Color (2017) *International Fungi & Fibre Federation (IFFF).* Available at: http://www.mushroomsforcolor.com/IFFF.htm (Accessed: 10 July 2021).
Mycelium + Timber (2017) [Exhibition]. London Design Festival 2017: Design Frontiers. 18-26 September 2017.
MycoWorks (2021) *Grow the Future of Materials.* Available at: https://www.mycoworks.com (Accessed: 10 July 2021).
Officina Corpuscoli (2021). Available at: https://www.corpuscoli.com (Accessed: 10 July 2021).
Park, S. and Ivanova, N. (2013) *MycoCouture: BioSuede.* Available at:

http://exploringtheinvisible.com/2013/02/26/mycocouture-biosuede/ (Accessed: 15 July 2014).
Rachman, S. (2004) 'Fear of contamination', *Behaviour Research and Therapy, 42 (11)*, pp. 1227-1255.
Rice, M.C. and Beebee, D. (1980) *Mushrooms for Color.* Eureka, CA: Mad River Press, Inc.
Rice, M.C. and Beebee, D. (2007) *Mushrooms for Dyes, Paper, Pigments and Myco-Stix™.* 2nd edn. Fort Bragg, CA: International Mushroom Dye Institute.
Robertson, O., Høgdal, F., McKay, L. and Lenau. T. (2020) *Fungal Future: A review of mycelium biocomposites as an ecological alternative insulation material.* Proceedings of NordDesign 2020, Lyngby, Denmark, 12th - 14th August 2020.
Rolfe, R.T. and Rolfe, F.W. (1925) *The Romance of the Fungus World.* London: Chapman and Hall
Sanders, E. and Stappers, P. (2008) 'Co-creation and the new landscapes of design', *CoDesign: International Journal of CoCreation in Design and the Arts, 4 (1)*, pp. 5-18.
Singh J. and Aneja K.R. (eds.) (1999) *From Ethnomycology to Fungal Biotechnology*. Boston, MA: Springer.
Spooner, B. and Roberts, P. (2005) *Fungi.* London: HarperCollins.
Stamets, P. (2004) *Mycelium running: how mushrooms can help save the world*. Berkeley, California: Ten Speed.
Stamets, P. and Chilton, J. S. (1983) *The Mushroom Cultivator: A Practical Guide to Growing Mushrooms at Home.* Olympia, Washington State: Agarikon Press.
Suri, J. F. (2007) *Involving People in the Process*. London: Include
Thackara, J. (2015) *How to thrive in the next economy*. New York: Thames & Hudson
The Future of Plastic (2014) [Exhibition]. Fondazione PLART, Napoli. 11 July – 27 September, 2014.
The Growing Pavilion (2019) [Exhibition]. Dutch Design Week 2019. Available at: https://thegrowingpavilion.com (Accessed: 11 July 2021)
Thompson, I., Stott, N. and Kerridge, T. (2006) *Biojewellery.* Retrieved from http://materialbeliefs.com/biojewellery/images/exhibit/biojewellery-booklet.pdf).
Tilbury, N. (2009) *Digital Skins - Body Atmospheres.* Available at: http://vimeo.com/9962212 (Accessed: 6 August 2014).
Trochmé, S. (2002) *Fabric.* London: Mitchell Beazly, Octopus Publishing Group Ltd.
Wainwright, M. (1992) *An Introduction to Fungal Biotechnology.* Chichester: John Wiley & Sons Ltd.
Willis, K. J. (ed.) *State of the World's Fungi 2018.* London: Royal Botanic Gardens, Kew.
Плесень (Mould) (2009) Directed by D. Vassilev [Video]. Russia: Masterskaya, Channel 1.